Meson Spectroscopy in Ultra-Peripheral Heavy-Ion Collisions at STAR

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Heavy Ion Meeting
KIAS, Seoul, 14th September 2006

PUSAN NATIONAL UNIVERSITY

BROOKHAVEN
NATIONAL LABORATORY

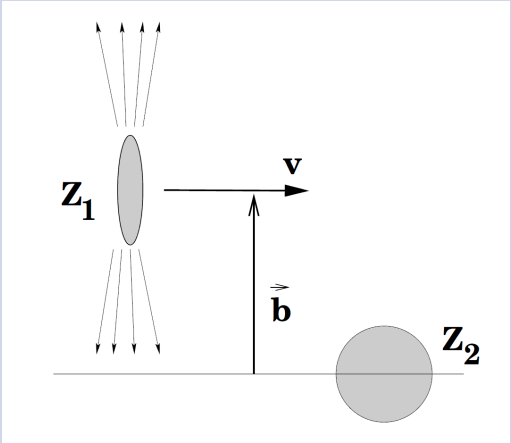
Outline

1. Introduction
   - Ultra-peripheral heavy-ion collisions
   - Vector meson production in UPC
   - Proof of principle — ρ production in UPC at STAR
2. Higher Quarkonia and Exotic mesons
   - Exotics defined
   - Experimental evidence for light exotic mesons
   - The ρ' meson(s)
3. Meson spectroscopy at STAR
   - ρ' cross section measurement
   - Future plans — search for exotics

Outline

Ultra-Peripheral Heavy-Ion Collisions (UPC)

- Nuclei "miss" each other geometrically: $b > R_1 + R_2$
- No nucleon-nucleon collisions
- Interaction via long range fields
- Nuclei stay (nearly) intact



- Strong electromagnetic fields ($\propto Z^2$) act for very short time
- High intensity beam of quasi-real virtual photons
- Photon exchange, photon-photon or photon-nucleus interactions
- Nuclear Coulomb excitation, e^+e^- pair and meson production, and vector meson production

This talk: **vector meson production in photonuclear interactions**

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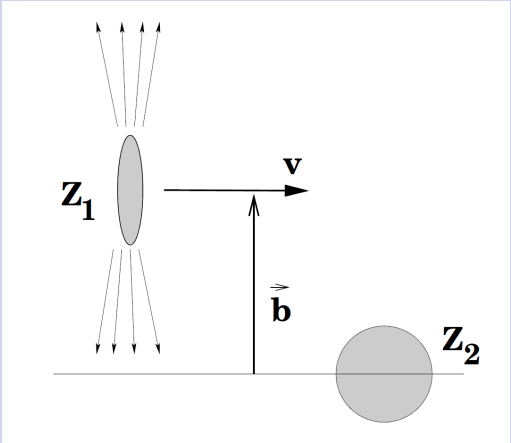

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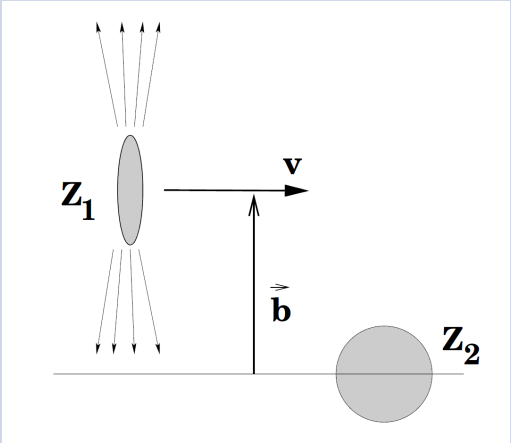

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Vector Meson Production in UPC

- Vector dominance: γ^* from "spectator" ion fluctuates into $q\bar{q}$ pair
- $q\bar{q}$ pair scatters elastically off "target" nucleus into real vector meson

Photon is diffractively excited to a vector meson

- Flux of γ^* described by Weizsäcker-Williams approximation
- Photon spectrum: $\mathrm{d}N\,/\,\mathrm{d}k \propto Z^2\,/k$
- Maximum photon energy in lab frame:
  $\omega_{\mathrm{max}}^{\mathrm{LF}} \approx \gamma\hbar c\,/\,R_A \approx 3\,\mathrm{GeV}\,(\mathrm{RHIC}), 100\,\mathrm{GeV}\,(\mathrm{LHC})$
- In rest frame of target nucleus:
  $\omega_{\mathrm{max}}^{\mathrm{target}} \approx (2\gamma^2 - 1)\hbar c\,/\,R_A \approx 600\,\mathrm{GeV}\,(\mathrm{RHIC}), 500\,\mathrm{TeV}\,(\mathrm{LHC})$
- Much higher energies than in fixed target experiments
- Diffraction is dominated by Pomeron exchange

Vector meson production in photon-Pomeron fusion

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Vector Meson Production in UPC

Coherent photon-Pomeron fusion

- Large cross section for coherent coupling of γ^* and $\mathbb{P}$ to extended charge $\Longrightarrow$ $\lambda_{\gamma,\mathbb{P}} > R_A$
- Coherence condition from uncertainty principle:
  - **Experimental signature:** low transverse momentum $p_T < \hbar c / R_A$
    $p_T \approx 30$ MeV/c for $R_A(\mathrm{Au}) \approx 7$ fm
  - Longitudinal momentum $p_{\parallel} < \gamma\hbar / R_A \approx 3$ GeV/c for $\gamma \approx 100$
- High photon flux + coherent scattering
  $\Longrightarrow$ large cross sections for vector meson production
  - E.g. $\sigma(\rho) \approx 590$ mb at RHIC, 5.2 b at LHC
- Relativistic heavy ion colliders are vector meson factories
- Study of C-odd mesons in photon-Pomeron fusion

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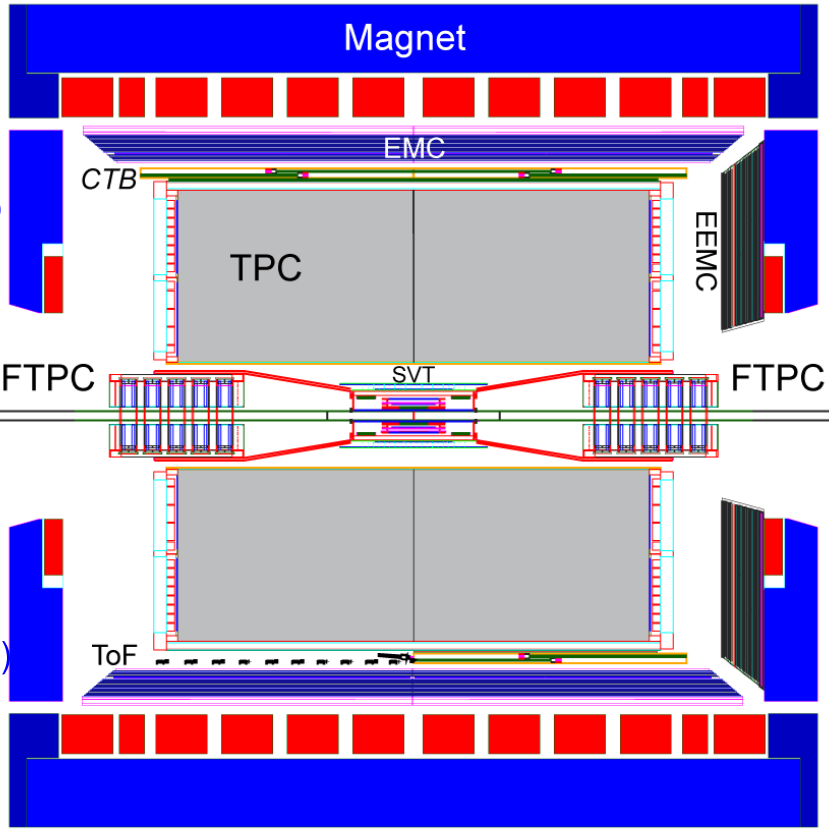
The STAR Experiment

Magnetic Field : 0.5 T

- Silicon Vertex Tracker (SVT)
- Time-Projection Chamber (TPC)
- Forward TPC(FTPC)



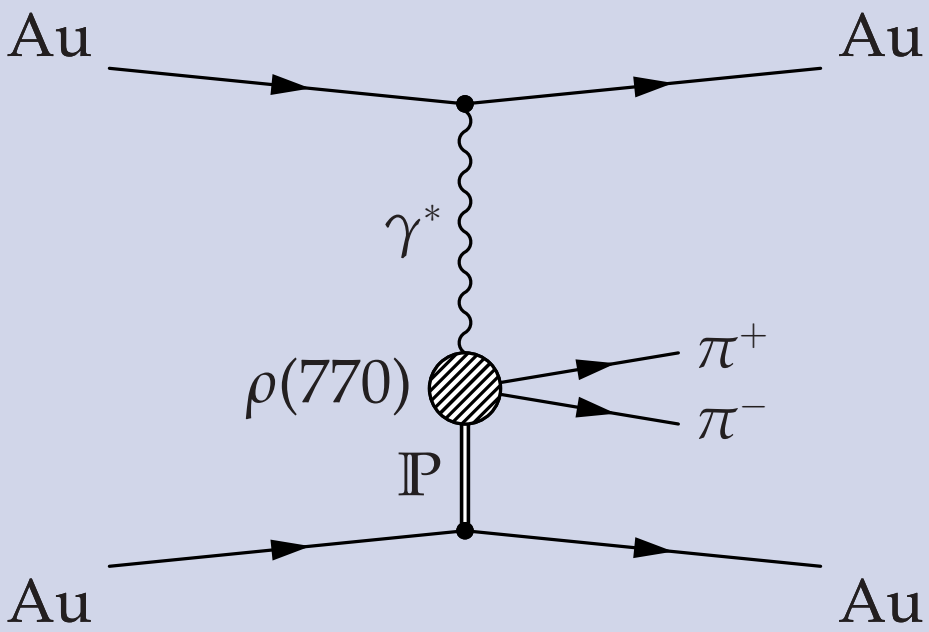
- Endcap EMC (EEMC)
- Zero-Degree Cal (ZDC)
- ToF (2008) ~ 85 ps
- CTB *to be removed*

- Central Trigger Barrel Counter (CTB)
- Time-of-Flight Detector (ToF)
- Barrel EM Cal (EMC): 4,800 Towers

Proof of Principle — ρ Production in UPC at STAR

Exclusive $\rho(770)$ production in coherent photon-Pomeron fusion

S. Klein *et al.* PRL **89**, 272302 (2002)



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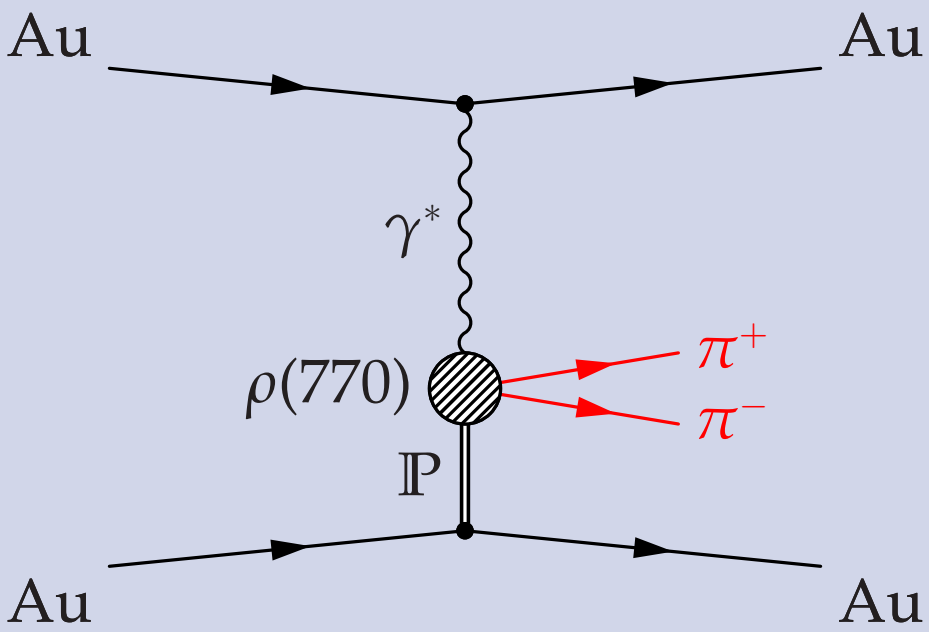
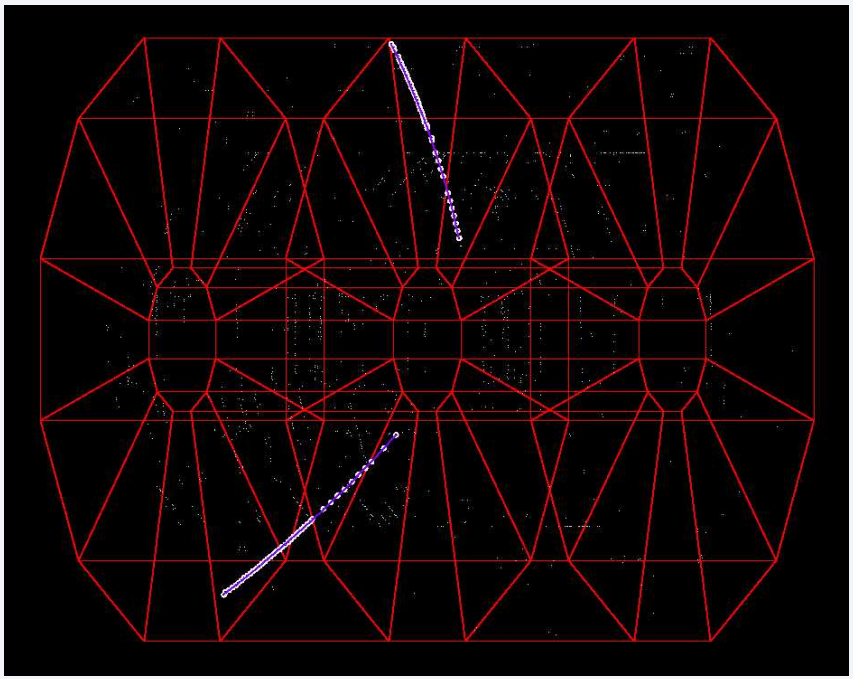


ρ Production in UPC at STAR — Experimental signature



Challenging trigger

- 2 oppositely charged tracks with vertex
- Low total p_T
- Back-to-back in transverse plane

Trigger: **Topology requirement in central trigger barrel** (CTB)

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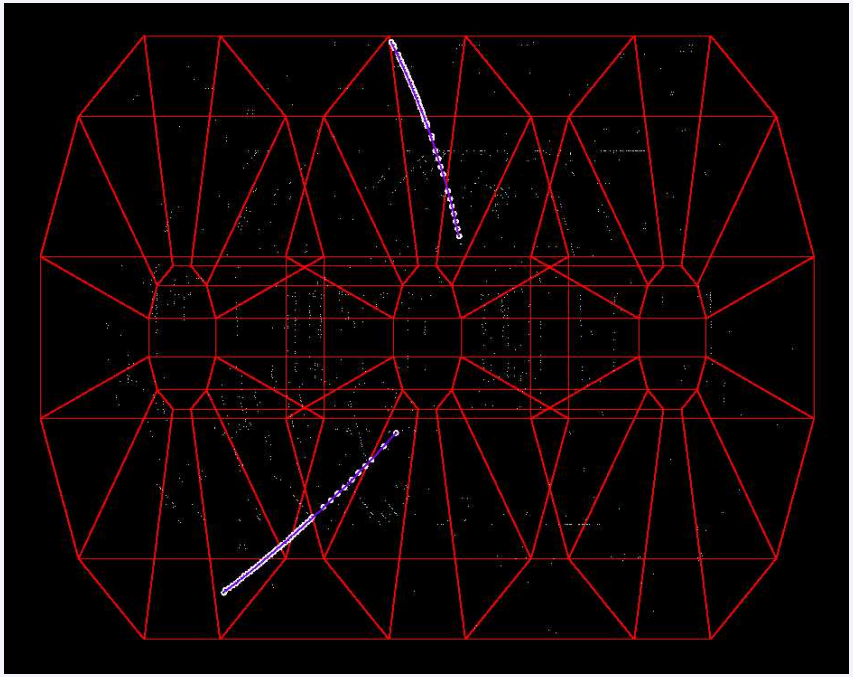

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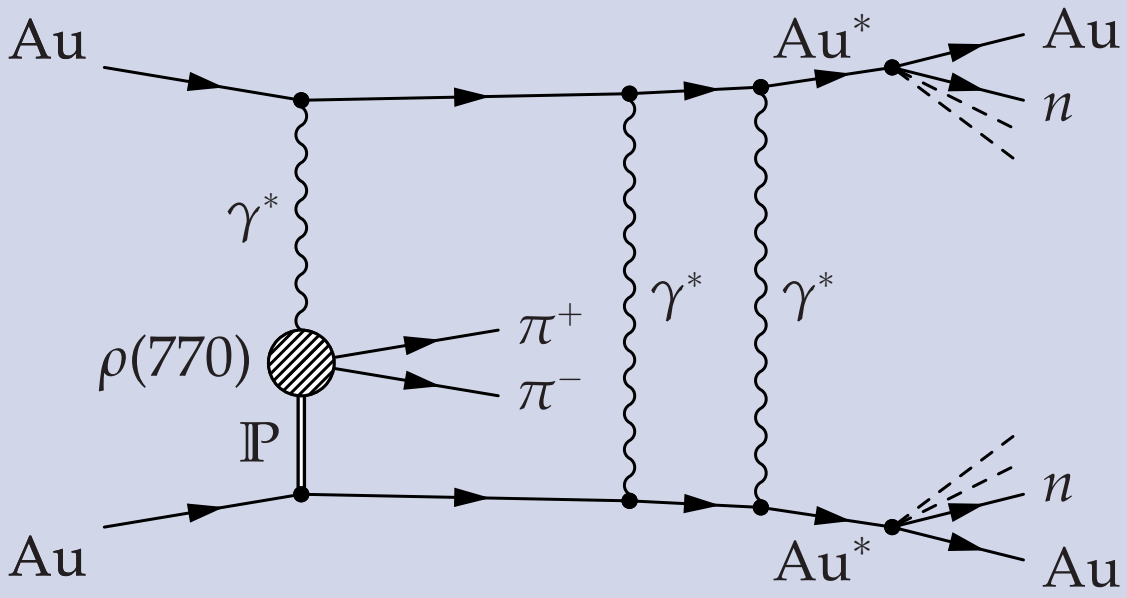

- High photon flux: multiple interactions between single ion pair
- Nuclear excitation into giant dipole resonance (GDR), independent of vector meson production
- GDR decays via neutron emission $\Longrightarrow$ detection with zero degree calorimeters (ZDC) $\Longrightarrow$ **tagging of UPC**

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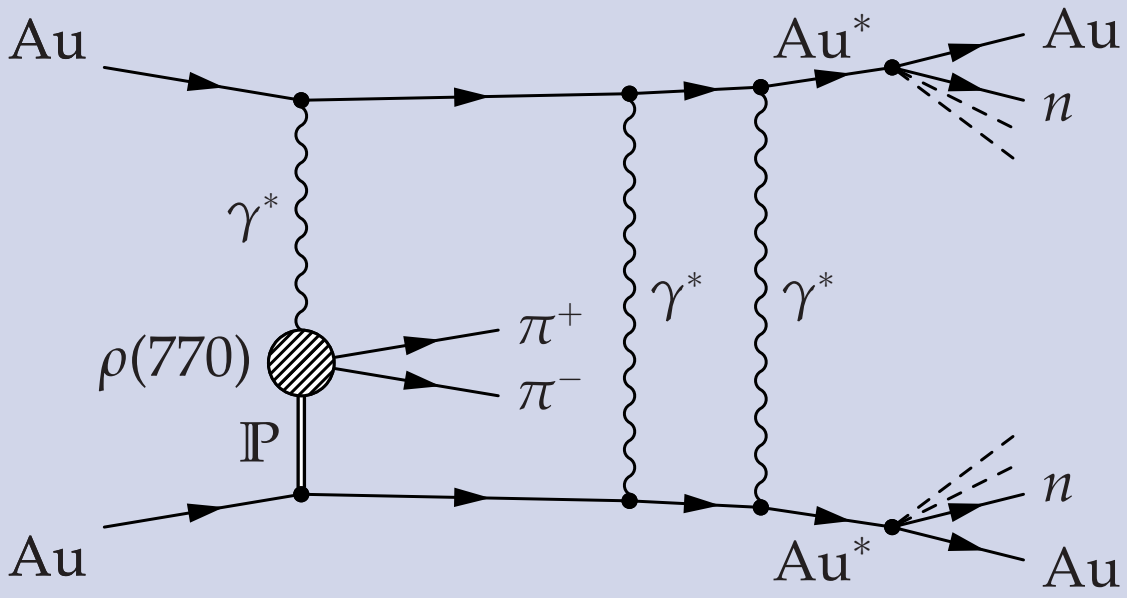

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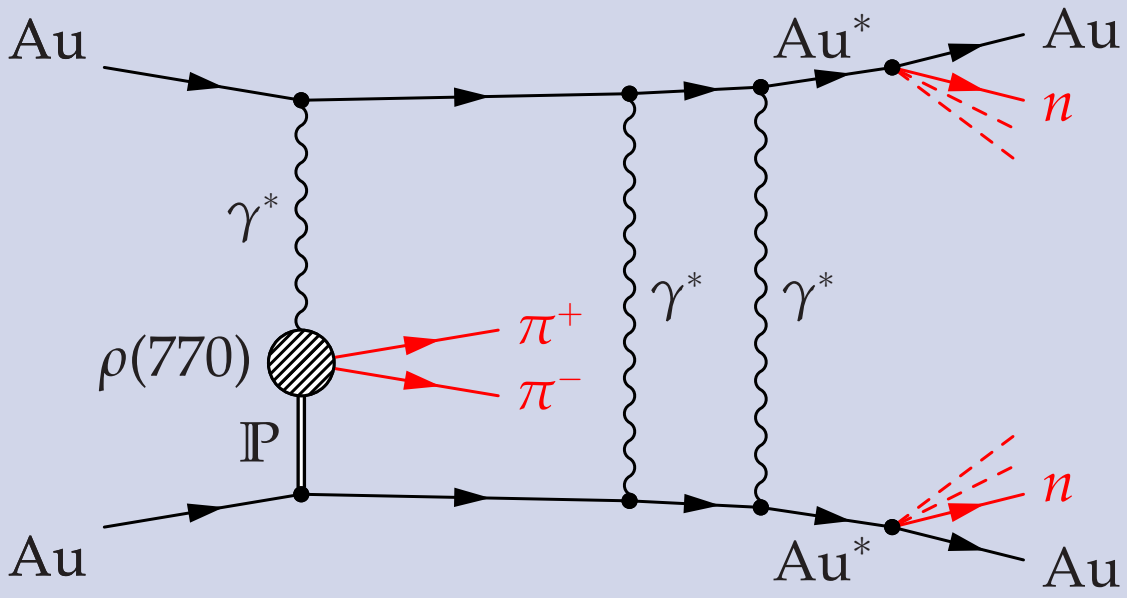

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ρ Production in UPC at STAR — Results

ρ production with nuclear excitation in Au $\times$ Au @ $\sqrt{s_{NN}} = 130$ GeV

p_T^ρ spectrum

Rapidity distribution

$\mathrm{d}\sigma(\rho)/\mathrm{d}M_{\pi\pi}$

- Total cross section: $\sigma_{\mathrm{tot}} = (460 \pm 220_{\mathrm{stat.}} \pm 110_{\mathrm{sys.}})$ mb
  S. Klein *et al.* PRL **89**, 272302 (2002)
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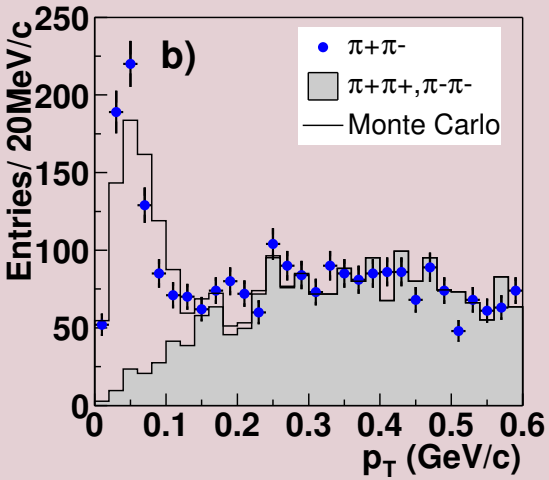

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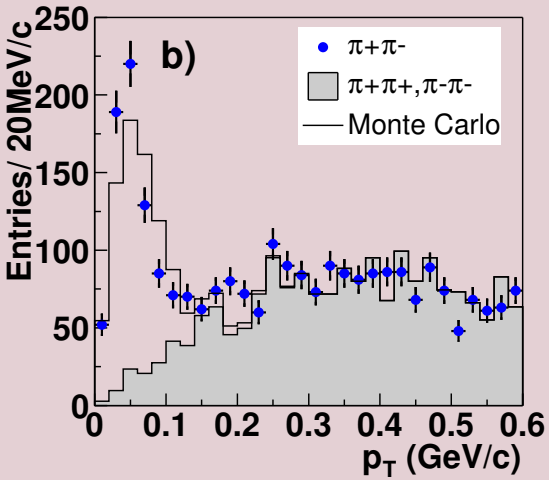

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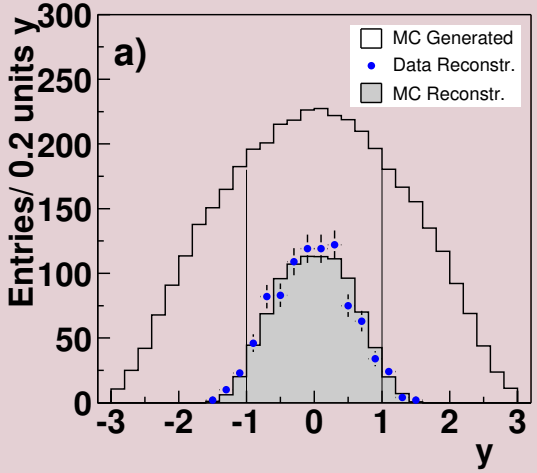

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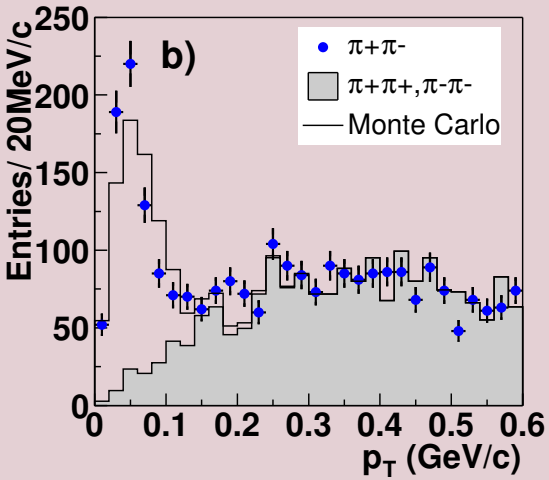

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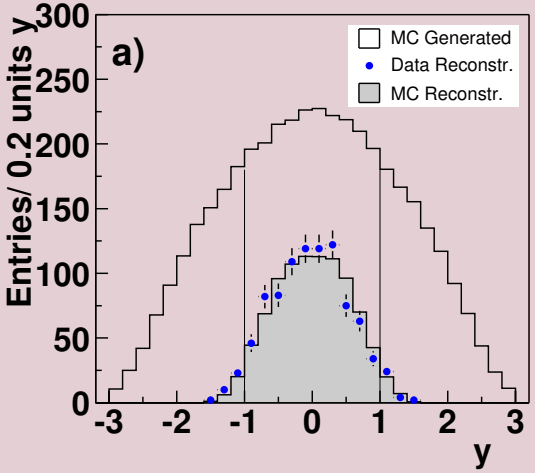

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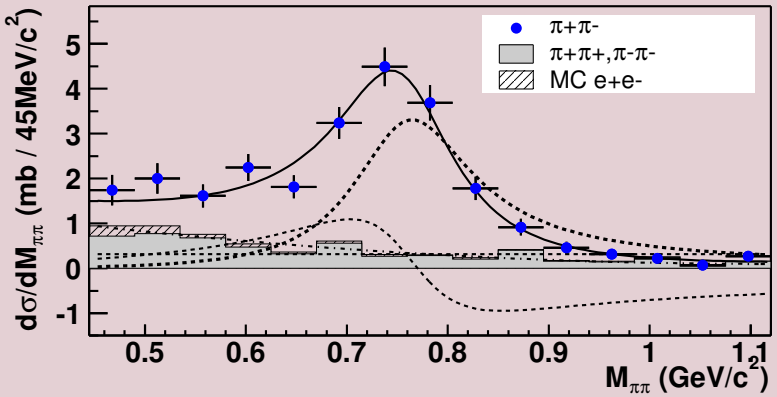

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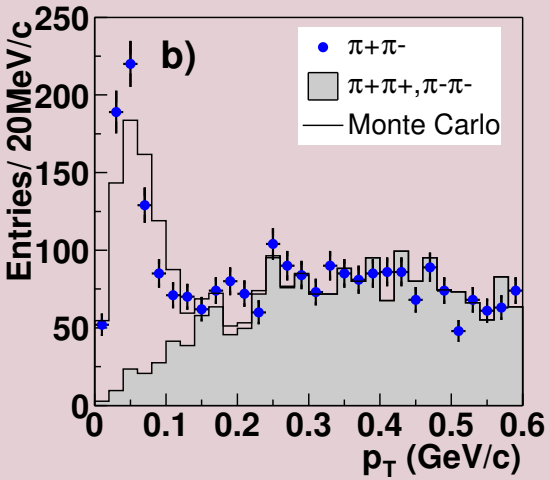

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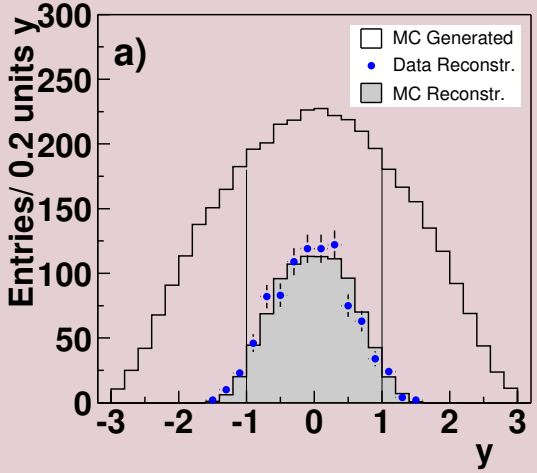

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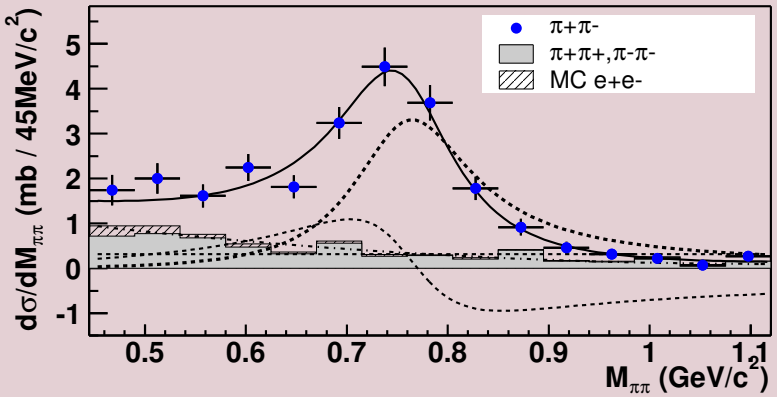

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Exotics Defined

Naïve constituent quark model

- Mesons are $|q\bar{q}\rangle$ states
- Total meson spin $\vec{J} = \vec{L} + \vec{S}$, total intrinsic spin $\vec{S} = \vec{s}_q + \vec{s}_{\bar{q}}$
- Parity $P = (-1)^{L+1}$
- C-Parity $C = (-1)^{L+S}$ (for neutral $|q\bar{q}\rangle$ states)

Forbidden J^{PC}: $0^{--}, 0^{+-}, 1^{-+}, 2^{+-}, 3^{-+}, \ldots$

Exotic meson

Has J^{PC} or flavor quantum numbers forbidden for $|q\bar{q}\rangle$ states in NRQM

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Extension of meson basis states

- Multi-quark states $|q\bar{q}q\bar{q}\rangle$
- States with valence glue $|q\bar{q}g\rangle$
- Bound gluon states $|gg\rangle$
- ...

- Mesons are linear superpositions of all allowed basis states
- Mixing amplitudes determined by QCD
- Amount of mixing is open question
- Classification into "quarkonia", "hybrids", and "glueballs" assumes dominance of one type of basis state
- Exotic mesons have no $|q\bar{q}\rangle$ component

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Exotics Defined

Naming convention for J^{PC} exotics

- Name determined by I^G and PC
  E.g.:

$I^G(J^{PC})$	$1^-(0^{-+})$	$0^+(0^{-+})$	$1^-(1^{-+})$	$0^+(1^{-+})$
Name	π	η	$\pi_1(1400)$	$\eta_1(1400?)$

$I^G(J^{PC})$	$1^+(1^{+-})$	$0^-(1^{+-})$	$1^+(2^{+-})$	$0^-(2^{+-})$
Name	$b_1(1235)$	$h_1(1170)$	$b_2(2000?)$	$h_2(2000?)$

Experimental Evidence for Light Exotic Mesons

J^{PC} exotic mesons identified so far

1. $\pi_1(1400)$: $m = (1376 \pm 17)\ \mathrm{MeV}/c^2,\ \Gamma = (300 \pm 40)\,\mathrm{MeV}$
   - $\eta\,\pi$ — BNL-E852 PRL **79**, 1630 (1997) and PR **D60**, 092001 (1999); Crystal Barrel PL **B423**, 175 (1998) and PL **B446**, 349 (1999)
   - $\rho\,\pi$ — Crystal Barrel NP **A721**, 605c (2003); Obelix EPJ **C35**, 21 (2004)
2. $\pi_1(1600)$: $m = (1653^{+18}_{-15})\ \mathrm{MeV}/c^2,\ \Gamma = (225^{+45}_{-28})\,\mathrm{MeV}$
   - $f_1(1285)\,\pi$ — BNL-E852 PL **B595**, 109 (2004)
   - $b_1(1235)\,\pi$ — VES NP **A663**, 596c (2000); BNL-E852 PRL **94**, 032002 (2005); Crystal Barrel PL **B563**, 140 (2003)
   - $\eta'(958)\,\pi$ — VES NP **A663**, 596c (2000); BNL-E852 PRL **86**, 3977 (2001)
   - $\rho\,\pi$ — VES NP **A663**, 596c (2000); BNL-E852 PRL **81**, 5760 (1998) and PR **D65**, 072001 (2002)
3. $\pi_1(2000)$: $m \approx 2000\ \mathrm{MeV}/c^2,\ \Gamma \approx 300\,\mathrm{MeV}$
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3. $\pi_1(2000)$: $m \approx 2000\ \mathrm{MeV}/c^2,\ \Gamma \approx 300\,\mathrm{MeV}$

$f_1(1285)\,\pi$	BNL-E852 PL **B595**, 109 (2004)
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Experimental Evidence for Light Exotic Mesons

J^{PC} exotic mesons identified so far

1. $\pi_1(1400)$: $m = (1376 \pm 17)\ \mathrm{MeV}/c^2,\ \Gamma = (300 \pm 40)\,\mathrm{MeV}$

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$\pi_1(1400)$ decay into p-wave $\eta\pi$ system

S. U. Chung, E. Klempt, and J. G. Körner EPJ **A15**, 539 (2002)

- *Assumption*: η meson is pure member of the pion octet
- Bose symmetrization: p-wave $\eta\pi$ system belongs to flavor $\mathbf{10} \oplus \overline{\mathbf{10}}$ representation
- *Assumption*: flavor SU(3) is conserved in $\pi_1(1400) \to \eta\pi$

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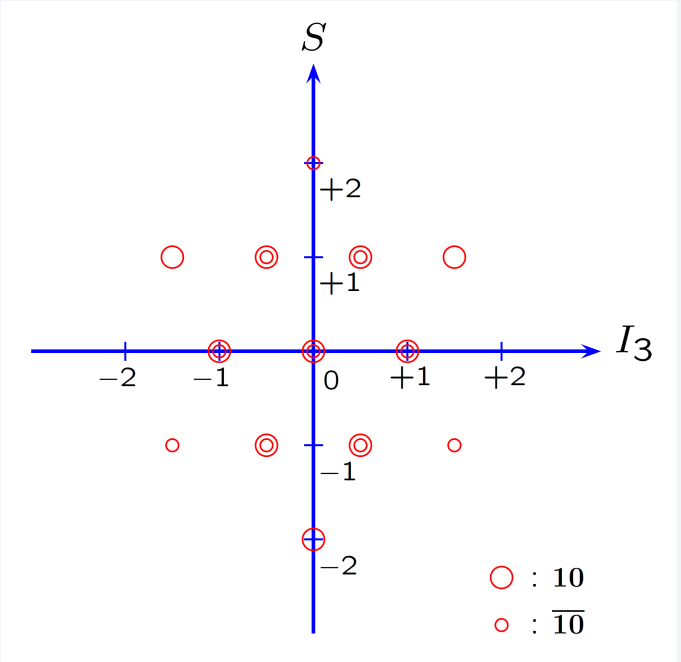

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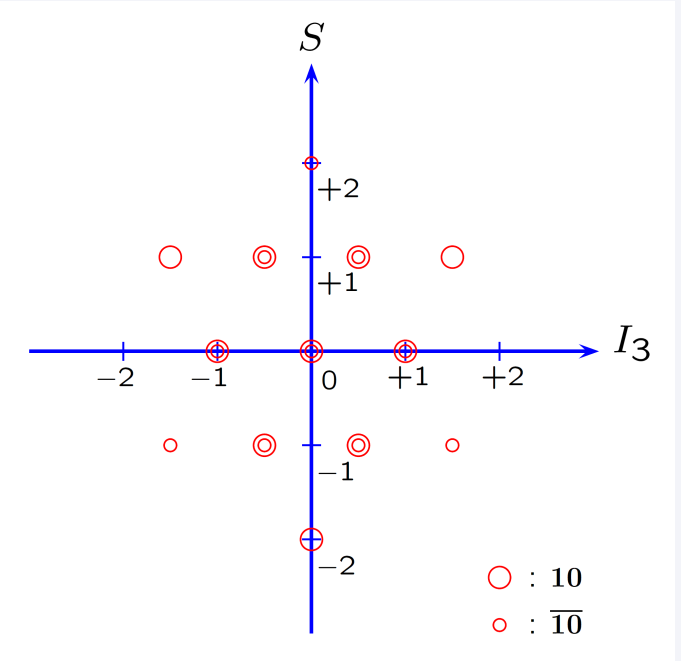

The ρ' meson(s)

Excited ρ states

- PDG: 2 poorly known states:
  - $\rho(1450)$: $m = (1459 \pm 11)$ MeV/c^2, $\Gamma = (147 \pm 40)$ MeV
  - $\rho(1700)$: $m = (1720 \pm 20)$ MeV/c^2, $\Gamma = (250 \pm 100)$ MeV
- Quark models predict 5 $|q\bar{q}\rangle$ ρ-like meson states below 2.2 GeV/c^2

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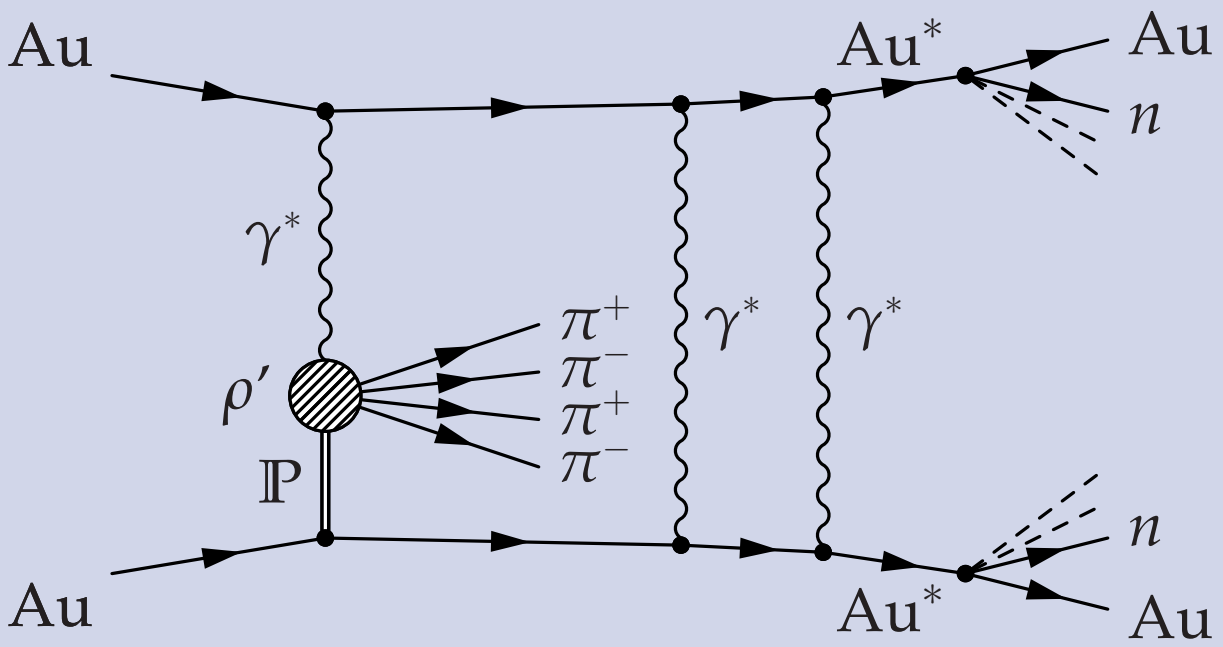
Outline

ρ' Production in UPC — Experimental Signature

ρ' production in coherent photon-Pomeron fusion with nuclear excitation



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- 4 charged tracks with $\sum_{\text{tracks}} Q = 0$ and $\sum_{\text{tracks}} p_T < 150$ MeV/c
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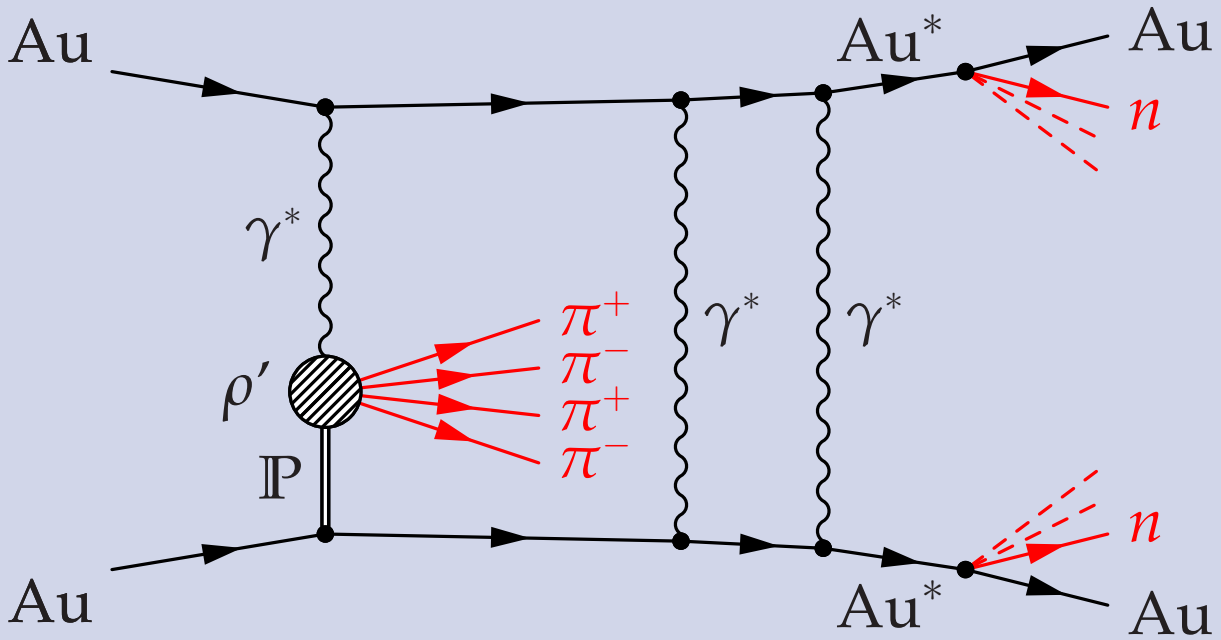

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Au × Au @ $\sqrt{s_{NN}} = 200$ GeV : 3.9 M 4-prong events

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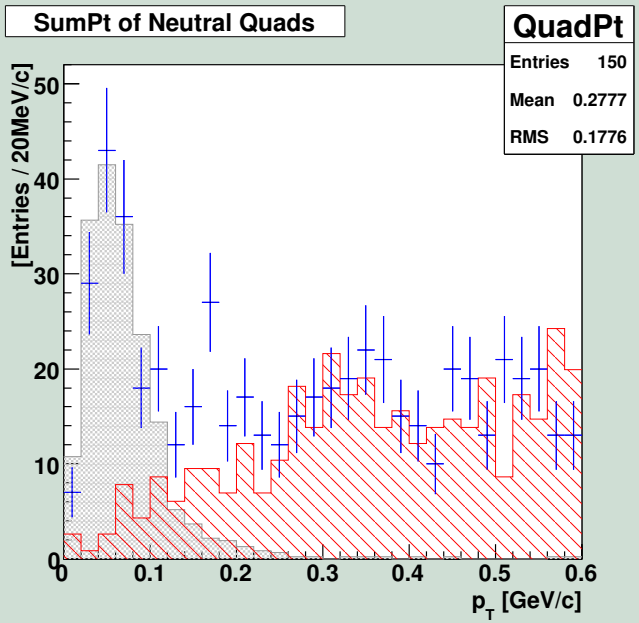

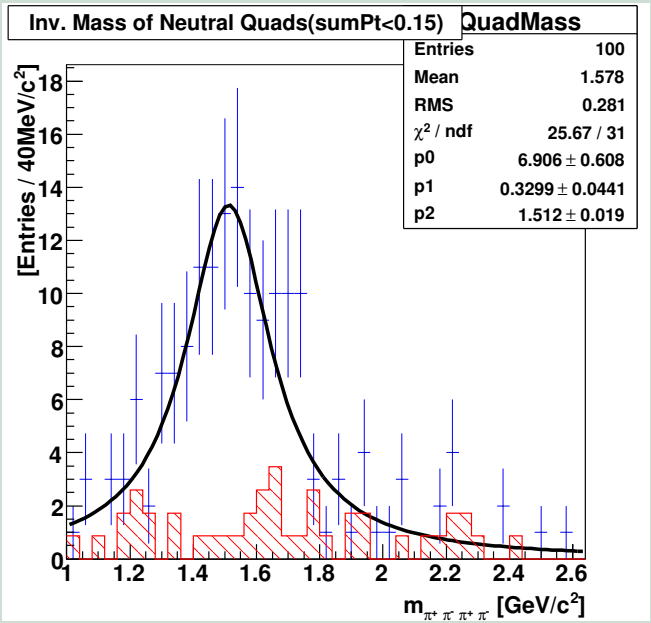

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Run 7 Au × Au @ $\sqrt{s_{NN}} = 200$ GeV : Measurement of ρ' cross section

- Expect to see $\approx 300\ \rho' \implies$ precision $\Delta\sigma/\sigma \approx 10$ %

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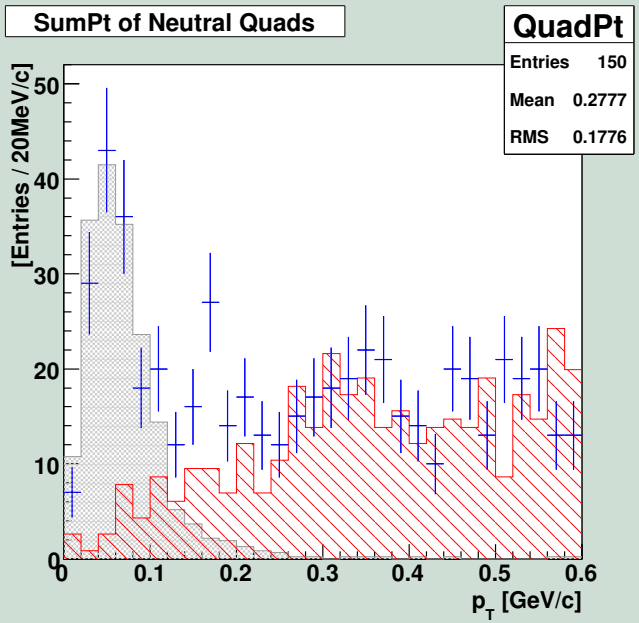

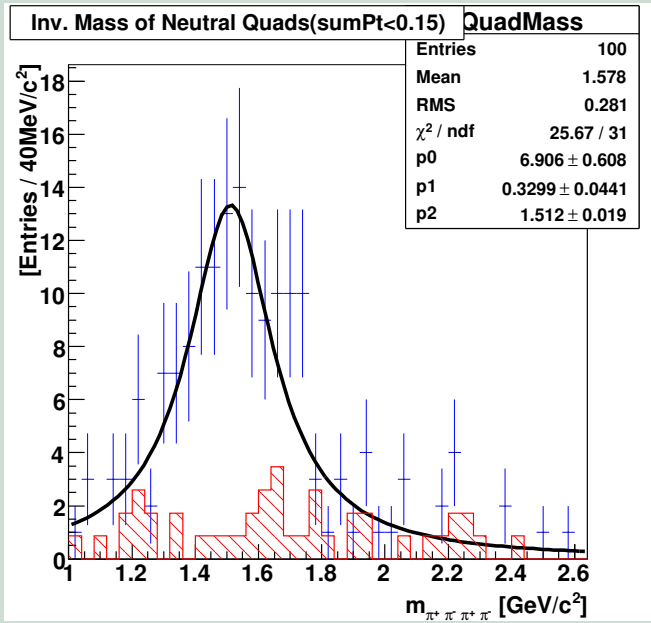

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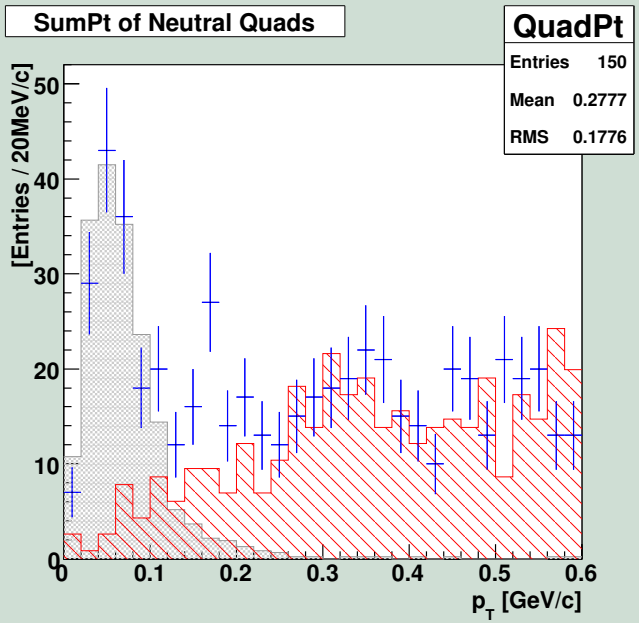

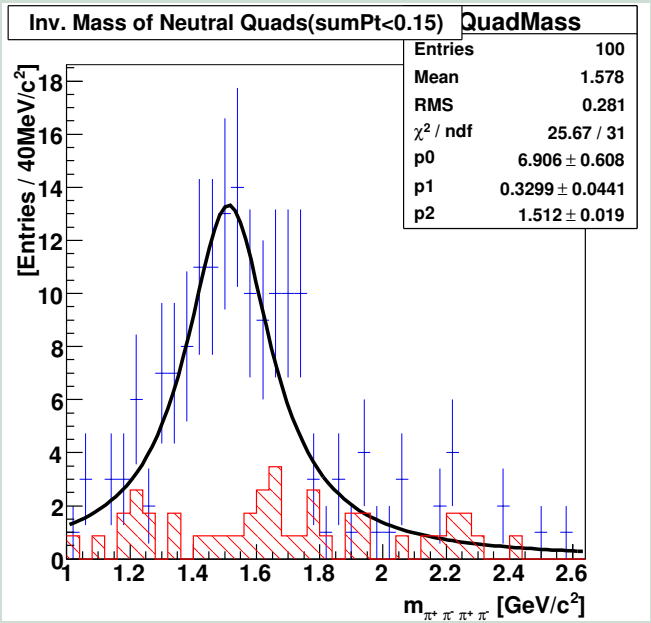

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Time of Flight (ToF) Detector

- Replaces central trigger barrel
- Multi-gap resistive plate chambers (MRPC) using ALICE technology
- 23 000 channels (6 slats $\times$ 32 plates $\times$ 120 trays)
- Full coverage of TPC acceptance (2π in ϕ, $|\eta| < 1$)
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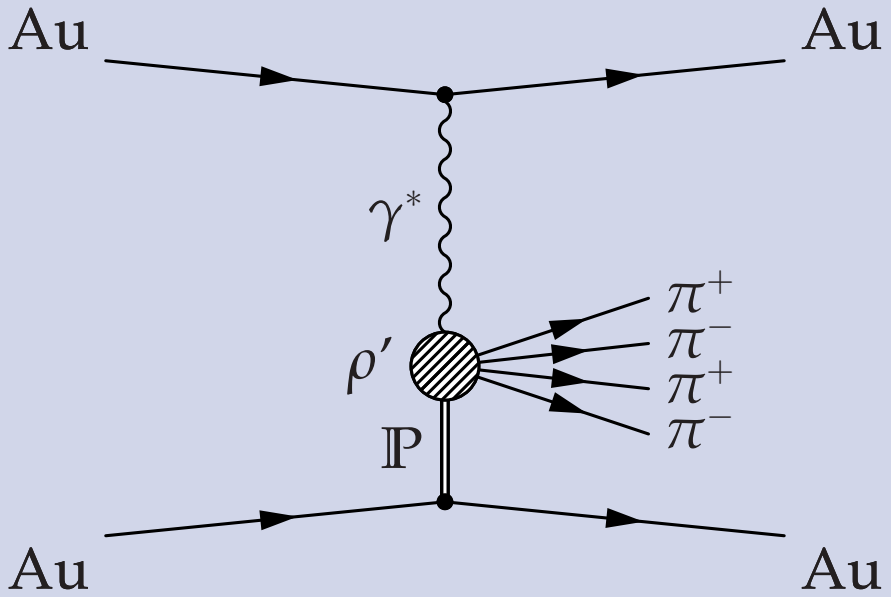

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Spencer Klein *et al.* PRL **89** (2002) 272302

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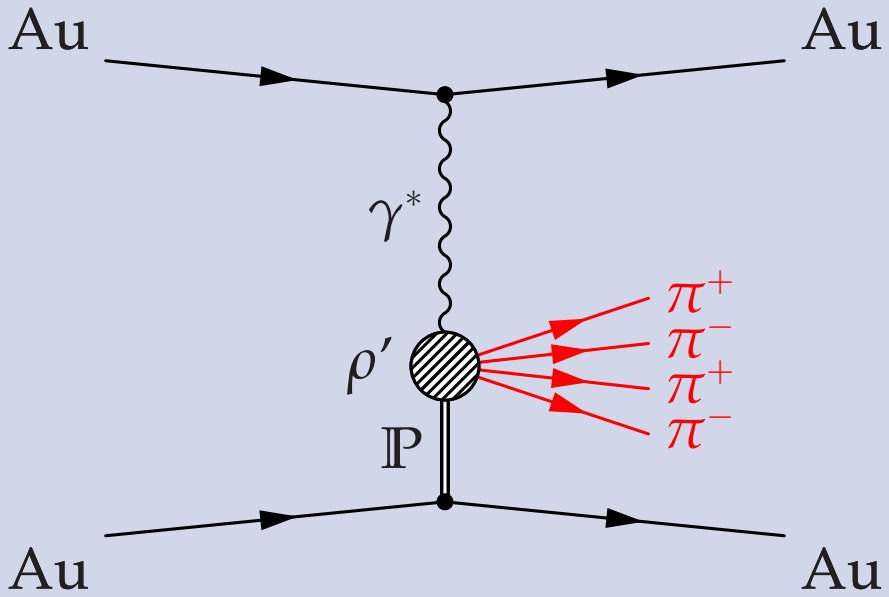

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Large ρ' sample

- Expect to see other heavy mesons produced through diffractive dissociation of $\rho(770)$ "beam"

Analogy: diffractive production of $a_1^-(1260)$ in $\pi^- p$ interactions

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- $\sigma[\pi^- p \to a_1^-(1260)\, p] \approx 4.3\,\%$ of $\sigma[\pi^- p \to \pi^- p]$

V. Flaminio *et al.* CERN-HERA **83-01** (1983)

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S.U. Chung, "Meson Production in Photon-Pomeron Fusion Processes", BNL Report

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Byoung-Chul Kim, PNU

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- Test of strong-field QED via e^+e^- pairs
- Multiple vector meson production
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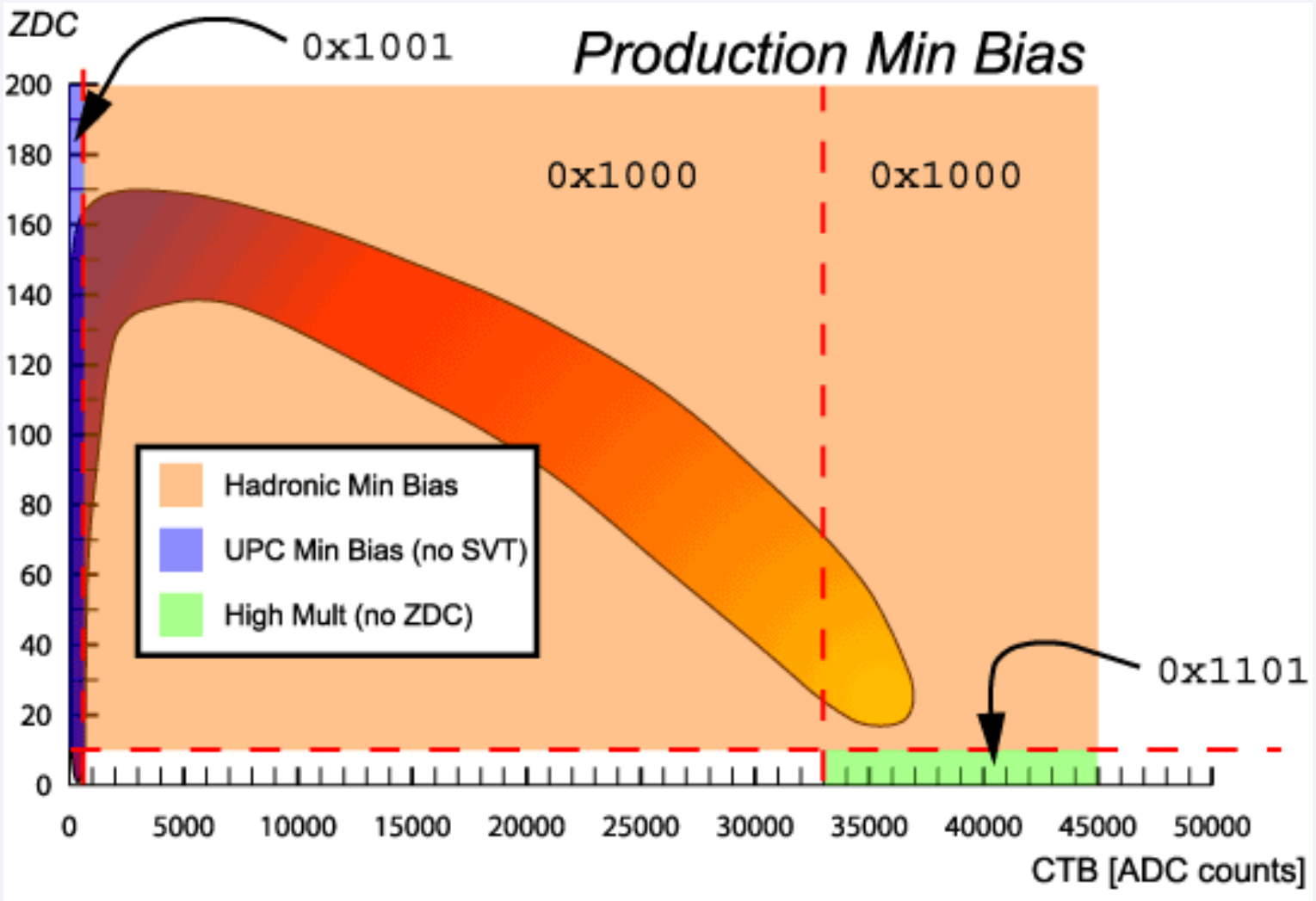
Outline

4-Prong Trigger



2-Prong Topology Trigger